APPLICATION

FOR

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FOR

FIBER OPTIC SENSORS FOR COMPOSITE PRESSURE TANKS

BY

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FIBER OPTIC SENSORS FOR COMPOSITE PRESSURE TANKS

This application claims the benefit of U.S. Provisional Application Serial No. 60/455,587 filed March 19, 2003.

BACKGROUND OF THE INVENTION

Lightweight composite SCBA (Self-Contained Breathing Apparatus) pressurized cylinders are in wide use in the firefighting, medical, aviation and transportation markets. S-2 glass/epoxy composite tanks 1 (Figs. 1-1 and 1-2) are used for life support gas cylinders, Kevlar/epoxy tanks 3 (Figs. 1-3 and 1-4) are used for life support as well as aircraft inflatables and oxygen supply applications. Carbon/epoxy tanks 5 are used for life support cylinders, recreational SCUBA and are proposed for alternative fuel vehicles (Figs. 1-5 and 1-6).

Composite pressure tanks are manufactured by overwrapping aluminum liners with hoop-wrapped or full-wrapped (axial + hoop) shells. The aluminum liner serves as an impermeable gas barrier and the composite shell provides the structure that resists the pressure, typically in the range of 3,000 to 4,500 psi. The U.S. Department of Transportation is responsible for the safe use of these tanks and normally requires a three-year cycle to hydrostatically test the structural integrity of composite tanks. Also, these tanks have a mandated retirement age of 15 years.

In 2001, Luxfer USA Limited introduced a full-wrap carbon-fiber/epoxy recreational SCUBA (Self-Contained Underwater Breathing Apparatus) tank 7 with DOT approval for a longer five-year retest cycle (Fig. 1-7).

Advantages of these tanks are light weight, corrosion resistance, dimensional stability, neutral buoyancy, and the ability to store roughly 30% more air than an equivalent all-metal tank. There is, however, a lower confidence level with the use of composite tanks than with metal tanks. The

fatigue mechanism in composite tanks that produces matrix cracking and eventual ply failures is more complex and less predictable than for metal tanks. Another problem with composite tanks is the potential for external surface damage that comes from the kind of rough handling to which SCBA/SCUBA tanks often are subjected. Composite pressure tanks currently are manufactured under DOT Exemption, TC Regulation 3FCM in the United States. Safety is a key issue. The ability to monitor structural integrity under a variety of operating conditions will be an important factor that determines future tank recertification intervals and tank life.

Composite tank manufacturing technology is here. What is needed is a means of insuring that composite tanks are as safe to operate as metal tanks.

SUMMARY OF THE INVENTION

The invention provides a Low-cost Fiber-Optic Sensor System for Composite Pressure Tanks to detect structural degradation of composite material pressure tanks. Light power attenuation in embedded optical fiber simulates tank volume change and replaces hydrostatic tank testing. Current U.S. Department of Transportation rules require that all pressure tanks be hydrostatically tested to verify structural integrity. This means that tanks have to be removed from service for testing. With the invention, testing can be done in-situ. For some applications such as composite LNG tanks used on vehicles or emergency inflation devices used on aircraft for escape ramps, etc., in-situ testing offers substantial maintenance cost savings. Also, because of the simplicity of the test procedure, more frequent structural checks can be made economically to improve the safe operation of composite tanks.

The invention is primarily for pressure tanks using a metal inner liner for sealing gas and an outer composite material overwrap for strength. The invention applies to any pressurized tank geometry. Cylindrical tanks with spherical or doubly-curved shell ends have immediate application.

A low-cost optical-fiber microbend sensor is used. A laser light source is attached at one end of the fiber and a light power meter at the other end of the fiber reads light power transmitted. Microbending is induced by allowing a length of fiber to cross over itself multiple times. Fiber-crossings produce pinch points that attenuate the light signal. As internal pressure is applied to the tank, radial pressure between the inner metal liner and outer composite overwrap squeeze the fiber. Where fibers cross at an angle, a stress concentration occurs that attenuates the transmission of light. With fiber crossings distributed over the surface of the tank, total light power attenuation will be an average measure of volume change of the tank.

Fiber crossing is achieved by wrapping and bonding a low-cost telecommunication optical fiber over the surface of the inner metal liner. For a cylindrical tank, this can be achieved by helically wrapping the fiber in a right-hand lay and then reverse the wrap with a left-hand lay. The lay angle is used to control the number of fiber crossings. The greater number of fiber crossings, the greater the light attenuation for a given internal tank pressure.

The technique to bond the fiber to the tank is important to the performance of the optical fiber sensor. If the adhesive is too rigid, fiber crossings might not produce sufficient signal (light power attenuation). If the adhesive is too flexible, light attenuation could become excessive, potentially resulting in a total loss of signal. Also, the type of adhesive determines the linearity of the light power signal. It is desirable that the change of light power attenuation for a change of internal

pressure vary linearly with tank volume change. Experiments have shown that certain adhesive materials give nonlinear signals and others give linear signals (polyurethane adhesives performed linearly; epoxy adhesives performed nonlinearly).

The means of applying the adhesive between the optical fiber sensor and the metal tank liner also is critical to the operation of the sensor and tank. If too much adhesive is applied, that could interfere with the bonding of the composite overwrap and the inner metal liner. The technique used to apply a very small amount of adhesive was to pull the fiber through a volume of uncured adhesive and then to remove excess adhesive by drawing the fiber through a long flexible tube with an inner diameter selected to remove a desired amount of adhesive. The thinly-adhesive-coated fiber is then helically wrapped onto the surface of a cylindrical tank under a tension designed to achieve contact pressure between the fiber and the metal liner. This is achieved by using a rotating mandrel. The desired lay angle is achieved by coordinating the rotational and axial feed rates.

To ensure that the fibers make sufficient contact at all fiber crossings, a shrink wrap tape is applied over the fiber. Heat is applied to both shrink the tape, thereby applying pressure to all fiber crossings, and to cure the adhesive.

The fiber ends are attached to optical connectors that are bonded to one end of the tank. In the case of the cylindrical metal liner, the connectors are bonded to the valve stem. Optical connectors of much smaller size than conventional connectors are a part of this invention. The fiber ends are stripped of their protective coating and epoxy-bonded into ceramic ferrules. The ends of the ferrules are polished and then placed into a metal housing with a protective metal cap.

The two connectors at each end of the optical fiber sensor then are bonded to the surface of the metal liner at a convenient location such as the valve stem.

After the fiber has been bonded to the surface, it is sufficiently ruggedized for shipping and handling without damaging the delicate fiber.

Finally, the tank with attached optical fiber sensor and optical connectors is over-wrapped with composite material using normal fabrication techniques. In the case of cylindrical tanks, this is accomplished by filament-winding the tank. The installation of the fiber optic sensor is economical and does not require composite pressure tank manufacturers to alter substantially standard fabrication techniques.

Tests of prototype cylindrical composite tanks prove that the embedded microbend sensor system successfully replicates conventional hydrostatic testing. It has been demonstrated that optical power light transmission can be made to respond linearly to tank volume change.

By integrating a simple, low-cost optical fiber sensor into the composite shell tanks can be checked easily for structural integrity each time the cylinder is refilled with gas. The opportunity to provide such continuity in structural health monitoring should have a significant positive impact on obtaining longer DOT certifications, extending product useful life, establishing buyer confidence and increasing sales.

The design challenge has been to create an embedded Fiber Optical Sensor System (FOSS) that can detect structural faults without precipitating structural degradation of the composite material. The manufacturing challenge has been to determine a means of integrating the sensor system into the tank fabrication process. The economic challenge will be to implement the FOSS into the manufacturing process without increasing cost by more than 5-10 %.

An embedded optical fiber microbend sensor, a modified type ST connector and a handheld optical laser and power meter constitute the optical sensor system that is used to monitor internal defects in the composite structure. Low-cost is obtained by using readily available optical components and a simple installation procedure, and robustness is provided by embedding the optical fiber sensor and encasing the optical connector in a metal housing.

Market research indicates that U.S. manufacturers alone produce in excess of a million composite pressure tanks each year. The British/U.S. firm, Luxfer USA, Ltd., produces approximately 3,000,000 composite gas cylinders per year. These products would benefit from an embedded sensor system. Discussions with Luxfer USA, Ltd. and Structural Composites Industries have indicated their interest in this technology, Luxfer has suggested that a likely initial application would be the pressure bottles used to inflate slides 9 on passenger aircraft (Fig. 1-8). It is expensive to remove these bottles for hydrostatic testing and an in-situ test that could be performed with the optical sensor should result in savings that total more than the cost of implementing this technology.

The microbend sensor system should simulate conventional hydrostatic tank testing where tank dilatation (volume change) is measured in response to internal pressure. By wrapping an optical fiber around the inner metallic liner of a tank, the optical fiber will be stretched along its entire length and subjected to microbending at locations where it contacts itself. This mechanical action must be designed to produce sufficient light power attenuation in response to applied internal pressure. The light attenuation will be a measure of the dilatation of the tank, and therefore can be used as a simpler replacement to conventional hydrostatic testing.

To evaluate the design, five prototype filament-wound composite cylinders were fabricated and tested. Methods of integrating the sensor system into the filament-winding process were investigated. Pressure tests of the prototype tanks checked sensor signal linearity and repeatability in response to tank internal pressure. Technical programs have demonstrated the technical feasibility of pressurized composite gas tanks with an integrated optical fiber sensor. Embedded optical fiber sensors will improve compliance with DOT certification criteria for composite air tanks, increase safety, extend product useful life, establish buyer confidence and increase sales.

These and further and other objects and features of the invention are apparent in the disclosure, which includes the above and ongoing written specification, with the claims and the drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Figs 1-1 thru 1-7. Composite tanks and their uses.

Fig. 1-8. Tanks in gas actuated escape ramps.

Fig. 2-1. Macrobending versus Microbending

Fig. 2-2. Microbending Test Results.

Fig. 2-3. 61° Two Layer Wrap with 52 Pinch Points

Fig. 2-4. 61° Four Layer Wrap with 202 Pinch Points.

Fig. 2-5. Pinch Test.

Fig. 2-6. Test Specimen.

Fig. 2-7. Cross-section of Pinch Point.

Fig. 2-8. Load Frame.

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DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

OPTICAL FIBER SELECTION

Optical fibers are manufactured for specific wavelengths of light that maximize light power transmitted through the fiber and minimize light loss as the fiber is bent. This approach is needed for telecommunication fibers where light must be transmitted over long distances. For an optical sensor,

however, a different approach must be taken. Since the sensor will function as a microbend sensor, an optical fiber that is sensitive to fiber bending should be used.

Three U.S. optical fiber manufacturers were contacted with a request for information on fibers having high bending sensitivity. None of the manufacturers were able to identify such a fiber, since they go to considerable effort to avoid bending loss. Clark and Smith (1995) discuss physical attributes needed for a good microbend sensor.

Fiber characteristics obtained from fiber manufacturers are described in Table 2-1. Data not available is indicated with NA.

Transmitted light power is lost in response to microbending. The very small bend radius associated with microbending diminishes power when the highest-order guided mode in the fiber core is coupled to the first cladding (radiation) mode, which then is rapidly attenuated. Figure 2-1 compares macrobending 11 and microbending 15. The curvatures of the bend fiber are very small, and very abrupt, for microbending (Fig. 2-1b) than for the more gentle macrobending (Fig. 2-1a).

Fibers are produced as single mode or multi-mode carriers of light. As shown in Fig. 2-2 (Clark and Smith, 1995), single mode fibers 17 are more sensitive to microbending than are multimode fibers 19. Numerical aperture is a good indicator of light loss for a bent fiber. The smaller the numerical aperture, the greater should be the light loss for a given bend radius. Table 2-1 shows that the Corning SMF-28 and SpecTran BFO4446 fibers have the smallest apertures. The Corning fiber has an acrylate coating, where the SpecTran fiber has a polyimide coating. Urruti et al. (1989) showed that the fibers with a polyimide coating show more vulnerability to microbending than did fibers having acrylate or silicone coatings. Thus, it would seem that the SpecTran might be the best choice for prototype development. The practical problem with the polyimide coating, however, is its removal

for joining with a ceramic ferrule. Stripping a polyimide coating requires dipping the fiber into heated sulphuric acid. Since a major objective of this program is to develop a low cost sensor implant, the higher cost of this coating and stripping of its ends is not justified.

The Corning SMF-28 fiber has a softer acrylate coating that is less sensitive to microbending, but its widespread use in the telecommunications industry makes it available at very low cost. Also, the fiber can be stripped mechanically at very low cost and a large selection of connectors for this fiber are available commercially. A potential problem with the acrylate coating is that it softens at nearly the same temperature needed to thermally cure the composite part. As the composite is helically wound around the fiber that is attached to the aluminum liner, large radial pressure acting on the fiber is produced. The combination of high radial pressure and high cure temperature (250°F) could cause the coating contact area between two crossed fibers to increase and therefore diminish microbend sensitivity. Microbend experiments described in a following section, however, show that microbend sensitivity is not reduced at the 250°F cure temperature.

The very low cost of the Corning fiber, the availability of many types of component parts that can be used in developing a connector, its low numerical aperture for microbending sensitivity, and its high mechanical strength (100 ksi) for handling the fiber during manufacture were critical characteristics that has made the Corning SMF-28 fiber the choice for prototype development.

ATTENUATION DUE TO FIBER STRETCH

An investigation was completed to determine if light power loss from axial strain of the optical fiber might be sufficient to function as a sensor.

A fiber manufacturer (Corning Optical Fiber Information Center) had conducted fiber tension tests that show insignificant light power loss for a very long fiber. For the SMF-28 fiber at the 1310 nm wavelength we are using, the optical attenuation caused by a 1% tensile strain over a 1 km length of fiber is only 0.2 dB. The light power loss in the prototype tested was about 0.3 dB for a very short length of fiber. This shows that the sensor signal was generated predominantly by microbending. Thus, the fiber stretch effect can be ignored.

SENSOR DESIGN

DOT TEST PROCEDURE

Fiber reinforced cylinders are to be hydrostatically tested in accordance with their exemption (see DOT-E7235, E9894, E9634 and TC Regulation 3FCM, 3HWM and SP3263). Composite cylinders manufactured in accordance with DOT Exemption and TC Regulations are to be hydrostatically tested at least once every three years.

The hydrostatic test requires the tank to be pressurized to its service pressure and its volumetric expansion measured. Upon release of the pressure, the tank passes the test if the permanent volumetric expansion is equal to or less than 5% of the total expansion.

TEST PROCEDURE

An embedded microbend sensor can be used as in indicator of tank dilatation during tank pressurization. Thus, if the residual light attenuation is equal to or less than 5% of the total light attenuation, the tank passes the test. The advantage is that the tank does not need to be transferred to a hydrostatic test facility. It can be tested on-site and its down-time therefore is minimized. With

this approach, the tank could be tested economically as frequently as each time the tank is filled with gas.

SENSOR LAYOUT

To create microbending, contra-helical layers of optical fiber are wrapped around the aluminum tank liner. Where the fiber crosses over itself at "pinch points", light power transmitted will be attenuated in proportion to internal tank pressure. The number of pinch points desired will depend on how the fiber is bonded to the liner (see Microbend Experiments below).

For this simple sensing scheme to work effectively, it is important to have a sufficient number of fiber pinch points 20 to cover effectively the surface of the tank. Too many pinch points, however, could reduce the output light signal to zero. Several lay patterns were investigated and the 61° double and quadruple wraps 21, 23 shown in Figs. 2-3 and 2-4 were finally selected for the prototype tanks.

The formula to predict the light power *output* is given by:

$$\textit{Percent Light Power Output} = 100(1 - X)^N \qquad (2\text{-}1)$$

where X = light power attenuation at one pinch point at a given radial pressure, and N = total number of pinch points. The value for X has been determined experimentally and is reported in the following section, Microbend Experiments.

The light power *loss* of a single fiber that crosses itself N times (N pinch points) can be found by the equation,

$$\textit{Percentage Power Loss} = 100\{1-(1-X)^N\} \tag{2-2}$$

MICROBEND EXPERIMENTS

Microbend experiments were conducted to simulate the optical signal generated in a crossed fiber embedded between the tank aluminum liner and composite overwrap. Figure 2-5 is a schematic of the test that was performed for a single pinch point 20. Light attenuation was measured 29 in response to an applied pressure 30. Light is input at end 25 and output at end 27.

The purpose of the microbend experiments is to obtain data on the sensitivity of the sensor for several different pinch point designs.

SPECIMEN PREPARATION

1 inch (25 mm) square specimens were prepared using an aluminum plate and an overwrap of E-glass/epoxy composite prepreg. Between the aluminum and composite material, a single Corning SMF-28 optical fiber 31 was crossed over itself at a single point 20 located at the center of the specimen. The fiber is bonded 33 to the aluminum surface 35, and then composite was laid over the aluminum. Figure 2-6 shows a single layer of composite 37 applied to a fiber pinch point. Additional layers of prepreg are applied to achieve the same thickness as the actual tank wall. Also visible in this figure is a circular mylar isolator 39 that shields the fiber pinch point from epoxy intrusion.

After all layers of composite are applied, the specimen is clamped at approximately 15 psi and cured at 250°F for 90 minutes. Heat-up and cool-down occurs at 5°F/min for a total cure time of 160 minutes.

PINCH POINT DESIGN

Figure 2-7 is a schematic of the cross-section of two contacting optical fibers 41, 43 embedded between the aluminum tank liner 45 and an overwrap of composite 47. As pressure 51 is applied at the inner surface 49 of the tank liner, the rigidity of the composite overwrap causes the overlapping fibers 41, 43 to pinch.

To control the optical signal (light attenuation across the pinch point), different filler materials 53 might be used or the interstitial volume around the pinch point 20 might be left vacant by use of an isolator film that covers and seals the pinch point. A softer filler material would permit more microbending and a stiffer material less. A hard filler, a soft filler and no filler (isolator) were investigated.

Epoxy Filler

The simplest approach is to allow epoxy to fully inundate the interstitial volume between fibers during the filament-winding process. This approach is the most economical since no additional steps in the manufacturing process are required. The fiber is coated with a thin film of epoxy (preferably the same as that used in filament winding) as it is wound onto the outer surface of the tank liner. After curing, the tank can be handled with less concern for fiber damage.

Polyurethane Filler

A softer polyurethane filler material was selected to confirm that the sensor signal would be increased. Again, to ruggedize the delicate optical fiber, it is coated with a thin layer of polyurethane as it is helically wrapped onto the outer surface of the aluminum liner.

No Filler (Isolator)

In this case, the optical fiber is dry wrapped onto the tank liner. Each pinch point is sealed by applying a circular mylar disk with adhesive backing to the site of each pinch point. This isolator can be seen in Fig. 2-6, just under the first layer of composite. This approach is expected to add cost to the process since application of the isolators is more involved. For example, it is not enough to position the isolators over pinch points, sufficient pressure must be applied to obtain a sufficiently good seal.

SPECIMEN TESTS

The specimens were tested in the load frame 57 shown in Fig. 2-8. Compressive pressure was applied to the microbend specimen by progressively tightening four bolts between the upper and lower platens. A load cell recorded the compressive force acting on the specimen, and a light source and power meter were used to measure light attenuation over the single microbend. A 1310 nm wavelength light source was used.

Figure 2-9 presents plots of the light power loss (in percent) versus the applied contact pressure for typical specimens. As expected, the epoxy filler produced the smallest, linear signal. The polyurethane produced a slightly larger signal that was predictably nonlinear. Use of the Mylar isolator produced by far the largest, nearly linear signal.

With the Mylar isolator, a 4% loss at a pressure of about 5 MPa (725 psi), 50 pinch points would result in a total light power loss of 87% (Eq. 2-2). Increasing the number of pinch points rapidly reduces the output light signal to zero. Where more pinch points are desired to provide a denser detection mesh for local breaks in the composite overwrap, either the epoxy or polyurethane-filled sensor would be recommended. For example, with a 0.75% loss with the epoxy filled sensor at the same 5 MPa pressure, 200 pinch points would result in a total tank loss of about 78%.

These experimental results indicate that the tank prototypes fabricated for this project should use 49 pinch points (Fig. 2-3) for the Mylar isolator and 202 pinch points (Fig. 2-4) with the epoxy or polyurethane fillers. Roughly then, each tank would loose about 80% of the light power at its maximum pressure.

FABRICATION

Figure 2-10 shows the prototype 60 with a two-layer helical wrap 21 of optical fiber 31 installed following the pattern in Fig. 2-3. Its installation involves cleaning and degreasing the surface of the tank, marking the helical path for the fiber, laying the fiber onto the aluminum liner and bonding the fiber to the tank. Long fiber sensor leads are left near the top for attachment to the connectors.

The fiber is bonded to the tank at an interval equal to the number of fiber pinch points 20. A Loctite cynoacrylate adhesive (LOCTITE Tak Pak 382) is applied near to, but not at, the fiber crossings. A curing agent is sprayed onto a fresh application of adhesive that hardens withing 5 seconds.

An optical fiber winding machine was designed and fabricated to improve the application of the fiber to the tank (Fig. 2-16).

A primary goal of this project has been to develop a low-cost, robust means of attaching the fiber optic sensor to the tank liner. Once applied, the fiber should be protected from mechanical damage when handling the tank prior to filament winding the composite overwrap.

A very low speed spindle (1-5 RPM) was designed to simplify installation of the optical fiber, application of the filler material and wrapping shrink tape over the sensor. Figure 2-11 shows a dry fiber sensor being helically wound onto an aluminum liner. The dry fiber is bonded to the tank liner as described in the previous section. This approach is used with Mylar isolators.

To bond the fiber to the liner and provide filler material that encapsulates each pinch point, the fiber is drawn through a syringe containing filler material. A flexible Teflon tip dispenses the fiber and acts as a low friction scraper that controls the coating thickness.

Figure 2-12 shows the applicator tip 71 (EFD UltraTip φ.014 x .5 long) with the emerging fiber optic sensor. The fiber 31 has an outer diameter of 0.008 inch. When drawn through the .014 inch diameter tube, the epoxy coating will have a thickness of .003 inch, sufficient to bond the fiber to the liner.

Figure 2-13 shows the applicator tip 71 and syringe 73 installed in a dispensing reel 75 that includes fiber tension control using a compression spring.

Figure 2-14 shows the applicator being used to apply the fiber sensor to the aluminum liner that is rotated on the low speed mandrel.

This application method performed well, requiring only 10-15 minutes to bond 52 feet of fiber to the aluminum liner. A production version of this device would include a horizontal feed mechanism to increase the application rate.

A free length at each end of the fiber is left near the neck of the tank liner for assembly to the optical connectors.

Next, shrink tape 79 coated with a release agent is wrapped over the installed fiber as shown in Fig. 2-15. The tank then is rotated under an infrared quartz heat lamp to both shrink the tape and provide a thermal cure to the filler material. The radial pressure produced by the shrink tape on the fiber improves the quality of the bond to the surface and ensures that the fibers are in contact at the pinch points.

At a temperature between 90°F and 150°F, the tape shrinks fully to produce a tensile tape stress, σ_t = 1,350 psi

The radial pressure, P_r, produced by a tape thickness, t = .002 inch, on the liner is calculated from the formula:

$$P_r = 2\sigma_t \, t \, N_L/D = 0.86 \text{ psi}$$

where the number of layers, N_L = 1, and the tank diameter, D = 6.28 inches. This pressure was determined to be sufficient to hold the fiber sensor in contact with the aluminum liner while curing. Figures 2-17 and 2-18 show the completed installation of fiber optic sensors with Mylar isolators and filler material, respectively. These tanks are ready for filament winding the composite overwrap. Because of the large light power attenuation with the Mylar isolators, the number of pinch points is limited to 49 (Fig. 2-17). The lower attenuation of the polyurethane or epoxy filler materials permits a larger number of pinch points to be used (202 points as in Fig. 2-18). These figures show optical connectors attached to the valve stem of the aluminum liner.

OPTICAL CONNECTOR

Development of an optical connector that terminates an embedded optical fiber sensor has been one of the more difficult aspects of this program. The connector must be sufficiently robust to survive rough handling of the tank and permit external instrumentation (laser light source and optical power meter) to be attached easily to the embedded sensor with minimal light power loss. Several design concepts were explored, including embedded and external connector concepts. The connector design was improved by simplifying its design and relocating the connector to the top of the tank and the final design and fabrication of the optical connector.

DESIGN OBJECTIVES

1. The overall length and diameter of the connector should be as small as possible to minimize the potential for mechanical damage.

2. The connector should function with a light wavelength of 1310 nm. Optical tests at this wavelength have provided the most stable readings for the Corning SMF-28 fiber.

3. The connector optical coupling loss should be significantly less than the optical signal produced by the microbend sensor.

4. The installation of the connector must be integrated into the filament-winding process without significantly complicating that process. Moreover, this integration must protect optical components throughout part processing.

5. The possibility of contamination of the connector optical components requires provisions for cleaning of optical surfaces.

Two connector concepts were investigated. One concept had the optical connector embedded in the composite shell wall. The advantage of this approach is that the connector is better protected from external damage; however, it also produces an inclusion in the shell wall that compromises the structural integrity of the tank. The second concept, used to fabricate a prototype, placed the connector in a housing that was attached to the bottom of the tank. This design functioned well optically, but the possibility of mechanical damage to the housing is greatest at the bottom of the tank. Also, this design is expensive to fabricate and install. A serious problem encountered with this design was fiber breakage that occurred during thermal curing of the part. A finite element analysis verified this assessment. A second prototype was fabricated and cured at room temperature to avoid this problem.

Figure 3-1 is a scaled solid model of the connector 80.

To ensure low optical power loss across the connector, a commercially available ceramic ferrule 81 with a split spring sleeve 83 designed for ST connectors was selected.

As seen in Fig. 3-1, the OFI (optical fiber interface) ceramic ferrule 85 is housed in a custom-made connector housing 87. The optical fiber sensor 31 enters the ferrule 85 at the left end. The ferrule is located at the center of the connector housing 87 by a close-fitting cylindrical bore 89. Epoxy potting material fills the counterbored void 91 around the fiber end (left end) of the ferrule 85 to seal the ferrule in the connector 80. This potting is accomplished while the external connector is attached to ensure mutual concentricity. At the right end of the ferrule, a larger counterbore 93 permits entry of the spring sleeve 83.

The external connector 95 is attached to a modified ST bulkhead coupler 97.

In practice, the coupler first is screwed onto the connector body. The external ST connector 81 then is inserted into the coupler with a quarter-turn action. A compression spring in the external connector provides sufficient pressure for its ceramic ferrule to contact the OFI ferrule, and the spring sleeve provides perfect concentric alignment between the two ferrules.

Modification of the bulkhead coupler consists of adding internal threads 99 to the left end of the coupler that mate with the connector body. The external threads on the connector body also can receive a protective cap 100 (Fig. 3-2). The cap is knurled for tightening by hand. A thin neoprene gasket inside the cap will seal the ferrule from water and other environmental contamination. The connector is just slightly longer than the ferrule so that the polished face of the ferrule is protected, yet still is accessible for cleaning.

CONNECTOR MOUNTING

Initially, it was envisioned that a metal mounting ring for the OFI connectors would be bonded around the valve stem. The valve stem is the turnaround pole for the axial layers of filament winding, however, and a mounting ring would increase the turnaround pole diameter. This larger diameter would create a structurally detrimental increase in the lay angle of the axial layers of filament winding. Therefore, an alternate mounting method was developed.

Instead of adding a mounting ring, two shallow cutouts 103 were machined directly into the valve stem 101 as shown in Figure 3-3. There is sufficient thickness in the valve stem 101 that the material will not fail under test pressures. For future production, the valve stem could be modified so that the cutouts can be made in an unpressurized area.

Figure 3-4 shows the OFI connector 80 bonded into the valve stem cutouts. The optical fiber exits the connector tangent to the valve stem and is helically wrapped around the valve stem down to the liner surface. A thin layer of potting material will be molded in place to protect the fiber that will not be covered by composite material and to seal the back of the connector. Figure 3-5 illustrates how ST connectors 81 are attached to the OFI connectors 95.

Since the mounted OFI connector protrudes from the valve stem it is susceptible to damage during normal handling of the tank. Therefore, the two-piece shield 110 shown in Figure 3-6 was designed to protect the connectors. The shield is assembled transversely to the axis of the tank. Two #10-24 cap screws 111 clamp the two sides 113, 115 of the shield to the pipe fitting. A rib 116 on the shield fits into the gap between the pipe fitting and the top surface of the valve stem to restrain the shield axially. A skirt 117 around the bottom of the shield encompasses the capped OFI connectors to protect them from damage. The shield must be removed to take a measurement. Figure 3-7 shows the fully assembled shield.

The size of the connector housing 95 is significantly smaller than a standard commercial ST connector. By using ST connector components, the SMF-28 fiber can be used, and light attenuation is comparable to commercial connectors. The connector design did not provide a polarized connection between the tank and external instrumentation. As two ceramic ferrules are rotated relative to one another, optical imperfections in the two surfaces cause a fluctuation in light power transmitted. The design depicted in Fig. 3-1 provides a repeatable and polarized connection.

After the fiber sensor is applied to the tank liner, the connector is attached to the fiber and then the connector is attached to the valve stem. The optical fiber is bonded to the liner along its entire length including the fiber leads to the connector. When the protective cap is attached to the connector

housing, the entire sensor is sufficiently ruggedized to permit handling and filament winding following current manufacturing procedures.

With the protective cap removed, the optical end of the ceramic ferrule can be accessed for cleaning.

CONNECTOR FABRICATION

CONNECTOR HOUSING

The connector housing 95 that attaches to the valve stem of the tank liner is shown in Fig. 3-8. The left end of the housing has a conical taper 121 to fit the mating slot 123 in the valve stem (Fig. 3-10). The right end is threaded to accept a knurled cap with a neoprene seal to protect the internal ceramic ferrule (Figs. 3-9 and 3-2). Fig. 3-11 shows how the housing mounts to the tank valve stem. The conical taper provides positioning of the housing such that the fiber sensor exits the housing exactly tangential with the surface of the valve stem.

COUPLER

A standard type ST bulkhead connector 124 was modified to fabricate the OFI coupler 125 shown in Figure 3-12. The right end of the connector was cut to reduce its overall length. The diameter was reduced to a diameter sufficient to remove the external threads. Finally, internal threads to match the threads on the connector housing were added to the right side of the bulkhead fitting. Assembly of the coupler and housing is shown in Fig. 3-14.

The left side of the Coupler can be attached to external optical cable as shown in Fig. 3-13.

FABRICATE CONNECTOR SHIELD

The completed connector shield described in Fig. 3-6 and Fig. 3-7 is shown in Fig. 3-15 and Fig. 3-16. The shield clamps to a hexagonal fitting at the top of the valve stem and provides protection to the two capped connectors shown in Fig. 3-15. The fully assembled shield is shown in Fig. 3-16. To access the connector, the shield is loosened and axially slipped off the fitting or the two halves can be separated.

Drop tests showed that this shield is effective in protecting the connectors.

SENSOR/FERRULE ASSEMBLY

The attachment of the ceramic ferrules to the Corning SMF-28 optical fiber sensor can be made only after the sensor has been bonded to the surface of the aluminum tank liner. This means that the ferrule must be attached to the length of fiber extending from the tank surface. The attachment involves stripping the acrylate coating from the fiber, inserting the stripped fiber through a ceramic ferrule, bonding the two parts, curing the adhesive in an oven, cleaving the fiber end near to the of the ferrule and polishing the end of the ferrule to an optical finish.

Each of these operations must be performed carefully to prevent breaking the stripped section of fiber, especially where the diameter is reduced from 125 µm to only a 6 µm core diameter. The fiber core is extremely delicate and is easily broken at the location where the acrylate coating was removed. Obviously, the free ends of the fiber must be long enough to allow one or two tries in assembling the ferrule and sensor. If this operation should be unsuccessful, the entire tank liner and fiber sensor would have to be discarded.

To minimize the possibility of fiber breakage, the procedure outlined below was followed.

After stripping a section of fiber, it was coated with epoxy adhesive (TRA-CON BA-F123) and inserted completely through the ceramic ferrule. A short length of the fiber end projects beyond the ferrule end. A small bead of epoxy develops at both the entry and exit points of the ferrule. This assembly is oven cured. After curing, the projecting fiber is scribed and separated. The end of the ferrule then is polished using the commercial Ultra Tec Minipol-2 fiber polishing machine 127 shown in Figure 3-17. The bonded fiber/ferrule is held stationary and an oscillatory rotating abrasive disk performs the polishing. This procedure resulted in a strong mechanical joint between the fiber and ceramic ferrule and an optically efficient polished fiber end that exhibited excellent light throughput. Light power loss through this connection was measured at less than 5%.

A manual polishing operation using a puck would risk fiber breakage due to the dynamics of trying to move the ferrule through a vigorous figure-8 pattern while the fiber is tethered to the surface of the tank. Instead, an automated polishing machine that keeps the fiber/ferrule stationary was used. Figure 3-18 shows a ceramic ferrule inserted in the lid of the polishing machine. When the lid is closed, its weight presses the end of the ferrule against a lubricated abrasive paper. Polishing proceeds through four abrasive grits (Fig. 3-19).

FERRULE/HOUSING ASSEMBLY

A commercial connector and the coupler (Fig. 3-12) are used to position accurately the ferrule inside the housing. The commercial connector is attached to the coupler as shown by the components on the left in Fig. 3-20. The ceramic ferrule (already attached to the optical fiber) is threaded through the housing and inserted into the spring sleeve (Fig. 3-1) contained in the coupler.

Next, a structural-rated epoxy adhesive (Hysol 9360) is inserted into the conical end of the housing (Fig. 3-21), and the housing is slid along the fiber and screwed onto the coupler (Fig. 3-22). A feeler gage is used to maintain a gap of 0.030 inch between the edges of the coupler and housing. After the epoxy cures in this configuration, and the housing is tightened fully against the coupler, pressure between the two mating ferrules will be developed by the compression spring in the commercial connector. Excess epoxy along the fiber is removed prior to curing.

This assembly is thermally cured at 180°F for one hour using the oven and temperature gage shown in Fig. 3-23.

Figures 3-24 to 3-26 are views of the completed attachment of the ceramic ferrule and connector housing.

INSTALL CONNECTORS

After attaching the connector to the optical fiber sensor, the optical leads are wrapped around the tank and valve stem to locate the connectors near the stem grooves (Figs. 3-3 and 3-10). Figure 3-27 shows two connectors draped over the valve stem ready for bonding. The protective caps are installed on the housings to prevent contamination from the epoxy. The fit of the housing in the groove is designed so that the fiber exits the connector tangentially to the surface of the valve stem (Fig. 3-28). Epoxy adhesive (Hysol 9360) is placed in the groove and the connector housing is clamped and thermally cured at 180 °F for one hour as shown in Fig. 3-28.

Figure 3-29 shows how the fiber sensor has been wrapped around the valve stem and looped and bonded at the tank end. Also shown are water-tight caps that protect the connector optical ferrule

from mechanical damage and contamination during filament winding. Figure 3-30 is a view into the connectors showing the internal optical ferrules.

INTEGRATING SENSOR INSTALLATION AND FILAMENT WINDING

The optical fiber sensor and connector have been fully bonded to the aluminum liner as described in the previous sections. In this condition, they should be sufficiently rugged to allow the tanks to be handled and filament wound using standard manufacturing procedures. Also, by locating the connectors near the top of the valve stem, the stem still can be used as a turn-around for reversing the wind. To prevent the connectors from being contaminated by epoxy during filament winding, protective caps are used to seal the optical ferrule.

The sensor system was installed on the aluminum liner as described herein for four tank prototypes. The prototypes were transported from Hawaii to Utah to the fabricator. The tanks were handled and mounted in the filament-winding machinery without special precautions. Three of the tanks had perfectly functioning optical sensors. One tank had epoxy resin coat the protective caps. The fabricator attempted to use force to open the caps with a plier. This caused the connector housing to rotate slightly and break the optical fiber at its entrance point to the housing. Future winds will require that the protective caps be covered with a release tape during filament winding.

COMPOSITE TANK

The tank consists of an aluminum liner and an E-glass/epoxy filament-wound overwrap. The aluminum liner serves as a mandrel for filament winding and the primary seal for the pressurized gas. It has one end threaded to contain a pressure regulator valve. The composite overwrap provides the

primary strength to the tank. A fiber optic sensor is sandwiched between the liner and composite overwrap to monitor tank dilatation and optical connectors are attached to the valve stem.

OBJECTIVES

1. The overall size of the prototype tank shall be about 6 inches in diameter and 2 feet in length. This size is representative of a SCBA or SCUBA tank.
2. An optical fiber sensor embedded between the aluminum liner and the first composite layer must be sufficiently sensitive to allow accurate monitoring of the dilatation of the pressurized tank.
3. The tank must have at least a factor of safety on material failure of at least 2 for the maximum test pressure.

ALUMINUM LINER

The profile for the aluminum liner is shown in Fig. 4-1. Table 4-1 lists the coordinates for points on the profile. Also, the wall thickness variation from one point to an adjacent point is given.

The liner is produced by a hydrostatic spinning process. It is 21.9 inches in length and has a 6.28 inch outer diameter. The nominal wall thickness of the liner in the cylindrical region is 0.094 inches. In the end sections, the wall thickness varies as shown in Table 4-4, but is thicker than in the cylindrical region. This is necessary since only axial wraps of composite partially cover the ends. Where the aluminum is thinner in the cylindrical section, both axial and hoop composite wraps are provided.

GEOMETRICAL AND MATERIAL PROPERTIES

Geometrical and material properties of the composite tank are presented in Tables 4-2 and 4-6. The bottom, middle and top regions described in Table 4-2 refer to the nearly hemispherical bottom, the cylindrical region and the top of the tank containing the valve stem, respectively.

Material testing was not done on the E-glass epoxy composite to determine its specific material properties. Generic properties for E-glass epoxy were taken from Tsai (1992). Because of the uncertainty in these properties a safety factor of two will be used for the pressure test limit.

The properties are given in the tables below: The Tsai-Wu coupling coefficients were all set to -1.

FINITE ELEMENT ANALYSIS

The strength of a prototype tank was determined by finite element analysis (FEA) using the ANSYS FEA program. The results of this analysis were used to choose a safe pressure limit for the prototype tank pressure test. The tank was modeled with quadrilateral linear layered structural shell elements (SHELL99). This element has four midside nodes (for a total of eight nodes). There are six degrees of freedom at each node, x-y-z translations and x-y-z rotations. The finite element model (FEM) was created from the data presented in Tables 4-1 to 4-3. Nodes were placed on the outside surface of the liner. The varying tank thickness and number of glass/epoxy layers were defined by 22 real constant sets. The complete FEM is shown in Fig. 4-2. The analysis results given here are based on the final as-built geometrical properties of the tank.

Figures 4-3 and 4-4 show the layer stacking sequence for elements in the cylindrical section and at the tank ends, respectively. ANSYS measures the lay angle from the hoop or circumferential direction. The axial wrap ($\pm 12°$ from the tank axis or $\pm 78°$ from the hoop direction) consists of two

layers of E-glass/epoxy unidirectional ply that covers the entire surface of the tank except for small areas at the poles. The outermost layer is a hoop wrap (+87° from the tank axis or +3° from the hoop direction) that is wound only over the cylindrical section of the tank.

Rigid body motion restraints were applied to all the nodes on the open edge of the tank valve stem. These nodes were held fixed in x, y, z translation as shown in Fig. 4-5.

A uniform internal pressure was applied to all the elements. The pressure load was increased until a failure in one of the layers occurred. Analysis was done with the PCG solver.

The 6061-T6 aluminum liner approaches its yield strength of 35,000 psi at an internal pressure of 1,400 psi. The yielding begins on the inner surface at the tangent between the cylinder and the tank ends as shown in Fig. 4-6.

At 1,400 psi internal pressure, the maximum Tsai-Wu inverse strength ratio is 0.78. An inverse strength ratio of 1.0 would indicate a failure. The maximum value occurs in layer 4 at the bottom end of the hoop wrap layer as shown in Fig. 4-7.

The pressure between the aluminum liner and the first glass/epoxy layer is the pressure that would be applied to the fiber optic sensor pinch points. A radial pressure of 850 psi was calculated at that location (Fig. 4-8).

The pressure was increased further to determine when the E-glass/epoxy would fail. At an internal pressure of 1,750 psi both the Tsai-Wu inverse strength ratio and the maximum stress ratio were very close to 1.0. The Tsai-Wu ratio is shown in Figure 4-9.

In summary, the FEA indicates that the weak point in the tank is in the aluminum liner at the tangent of the cylinder and tank ends. The liner will yield at a tank pressure of 1,400 psi. At 1,400 psi the pressure between the liner and the first E-glass/epoxy layer is 850 psi. The prototype tank pressure

test was limited to one-half of the predicted failure load because of the uncertainty of the E-glass/epoxy material properties. Assuming a linear response, an internal tank pressure of 700 psi should produce about 425 psi of pressure on the fiber optic sensor.

A composite tank with an aluminum liner has been designed using the ANSYS general purpose finite element software. The overall size of the prototype tank (aluminum liner and composite overwrap) is 6.76 inches in diameter and 21.9 inches in length. The profile of the liner is shown in Fig. 4-1. The valve stem has an industry standard 7/8-14UNF-2B thread.

The aluminum tank liner is expected to yield first at an internal tank pressure of approximately 1,400 psi. At 1,750 psi, matrix cracking of the composite overwrap would be expected since the Tsai-Wu Inverse Strength Ratio approaches unity. This does not imply failure of the tank. What the ANSYS analysis tells us is that we might begin to notice a nonlinear behavior of tank volume change with pressure above about 2,000 psi. Also, we might expect to see a residual (permanent) volume change when the tank pressure is relaxed to zero.

The design described in the foregoing satisfies all design criteria. All tank prototypes were manufactured according to the specifications presented.

FABRICATION

TANK LINER WITH OPTICAL SENSOR

Figures 4-10 to 4-15 show each tank prototype with an installed optical sensor.

Tanks 1 and 2 have 49 pinch points that were spot bonded to the surface of the aluminum liner with a cynoacrylate adhesive. Pinch points were not bonded. The fiber was hand-wound. Care was used in transporting, handling and filament winding these two tanks because of the relatively loose optical

fiber. During filament winding, the pinch points were bonded with epoxy. Radial pressure produced by filament winding kept the optical fibers in contact at the pinch points.

Tanks 3-6 were wound using the fiber optic winding machine.

Tank 3 has 53 pinch points sealed with Mylar isolators. Between pinch points, the fiber was bonded to the tank liner with epoxy (E.V. Roberts Resin Formulators RF-5001/RF-66). The resin was applied with a pressure injection syringe and flexible Teflon application tip. Excess epoxy was removed with a flat silicone squeegee. The cylindrical surface of the tank was wrapped with one wrap of thermal shrink tape (Airtech Dahlar MLF 521.25). A heat gun was used to shrink the tape. The resulting radial pressure held the fiber in intimate contact along the liner and at the pinch points. The epoxy was thermally cured with a thermal blanket at about 120°F for at least 8 hours.

Tank 4 has 202 pinch points with each pinch point bonded to the liner with Shore 70A polyurethane (E.V. Roberts Resin Formulators RF-1735). Between pinch points, the fiber was bonded to the tank liner using the same techniques as was used for Tank 3.

Tanks 5 and 6 both have 202 pinch points that are fully bonded with epoxy. The fibers were coated with the same epoxy resin used for Tank 3. Since the epoxy is a two part system, when mixed, air is entrained in the mixture. To remove the air, the epoxy was degassed in a strong vacuum (29.95 inches Hg) for 15 minutes. Epoxy was applied to the fiber by pulling the fiber from a reel through a syringe filled with the epoxy and then through a flexible Teflon dispensing tip (EFD 5125PPS-B with .014 inch inner diameter, ½ inch long). Figure 2-14 shows the process. Using the dispensing tool, the fiber was wrapped onto the liner using the fiber winding machine (Fig. 2-11). Two layers of shrink tape were applied (Fig. 2-15), and a heat gun was used to shrink the tape. This process is needed to ensure that the fibers are in intimate contact with the liner and at pinch points.

FILAMENT WINDING

After applying the fiber optic sensor, each tank was carefully packed in molded foam for shipping to the fabricator. Upon arrival at the fabricator's facility, each tank was checked for damage. No damage was found and the optical systems were functioning properly.

Each tank was wound according to the ANSYS finite element model given in the previous section. The procedure is described below.

The aluminum liner with fiber optic sensor is attached to the winding machine by a 2 inch diameter mandrel that threads into the valve stem of the tank liner (Fig. 4-16).

To reduce thermally induced stresses, a room-temperature curing epoxy was used with E-glass fibers. The glass fibers were run through an epoxy bath and then through tensioning fingers. The winding machine was programed to wind the four composite layers to the thicknesses determined by the finite element analyses. Figure 4-16 shows the beginning of the ±12° axial winds. Figure 4-17 shows the progression of the axial winds and Fig. 4-18 shows the completed axial wind.

Figure 4-19 shows the start of the 87° hoop wind. For this step, the machine must be stopped and the composite tow repositioned.

Figure 4-20 shows the progression of hoop wind. Excess epoxy must be removed as the part begins to cure at room temperature (Fig. 4-21).

After completing the hoop wind, the protective caps are removed from the connector and the fiber sensor is checked for optical continuity. All tanks passed this continuity check.

Tank 1 experienced a fiber failure when it was thermally cured at 250°F. The failure was due to the fiber being imbedded in polyurethane. With a higher coefficient of thermal expansion, the

polyurethane volume stretched the optical fiber sufficiently to fail the fiber. This mechanism was confirmed by a finite element analysis of the connector.

Because of the problem with Tank 1, the connector design was modified and a 24-hour room-temperature curing epoxy system was used. These corrections solved this problem.

The Tank 5 fiber optic sensor failed due to fabricator error. For this tank, the fabricator neglected to cover the connector protective caps with a release tape. While performing the hoop wind, epoxy resin coated the caps and effectively bonded the caps to the connector. Without notifying us first, the technician forced the caps loose by using pliers. We believe that this caused the connector body to rotate sufficiently to break the optical fiber at the point where it enters the connector body.

COMPLETED TANKS

Figures 4-22 to 4-27 show the completed tanks. Tanks 1 and 2 have 49 epoxy-filled pinch point. The fiber sensor in Tank 1 was damaged in thermal curing and could not be used for optical testing. Tank 3 has Mylar isolators covering 52 pinch points. Tank 4 has 202 polyurethane-filled pinch points and Tanks 5 and 6 have 202 epoxy-filled pinch points. During filament winding of Tank 5, epoxy was allowed to coat the protective caps. The optical fiber sensor was broken when technicians attempted to remove the caps forcibly with pliers.

Although Tanks 1 and 5 were used for hydrostatic testing, only Tanks 2, 3, 4 and 6 were tested for both volumetric and light power response.

The connectors on Tanks 2, 3, 4 and 6 all worked well. The Tank 2 connector lacked polarity and had to be calibrated for each test performed. The remaining tank connectors had polarity and provided consistent signals.

All the tanks were filament wound using the same lay angles and same E-glass/epoxy composite material. Tank 1 was thermally cured which caused the fiber sensor to break inside the connector housing. For this reason, all subsequent tanks were cured at room-temperature. Tank 2 differed structurally with the hoop wrap being only one-half that of the other tanks.

PROTOTYPE TANK TESTS

A series of tests were performed on six prototype tanks including low pressure and high pressure tests of the optical fiber sensor and hydrostatic volumetric tests. The optical fiber tests were performed in-house and the hydrostatic volumetric tests were performed at a tank test facility.

FIBER OPTIC SENSOR TESTS

Low and high pressure tests were conducted on the prototype tanks to measure the response of the fiber optic sensor to a change in internal pressure. Figure 5-1 illustrates the pressure test schematically. A manually operated hydrostatic test pump pressurized water from a hose inlet pressure of about 60 psi to an internal tank pressure of 1,000 psi for the low pressure tests or about 4,500 psi for the high pressure tests.

Finite element analysis of the as-built tank shows material yielding of the aluminum liner at a tank internal pressure of about 1,400 psi. Initiation of matrix cracking in the composite overwrap is predicted at about 1,750 psi. The location of material failure is at the tangent point between the tank ends and the cylindrical section of the tank. These predictions are based on approximate composite material properties. From the finite element analysis study, the prototype tanks are expected to exhibit

nonlinear behavior somewhere between 1,500 psi and 2,000 psi as the aluminum liner begins to yield and the composite matrix material (resin) begins to crack.

To ascertain a safe tank pressure for conducting these tests, Tank 1 was hydrostatically tested at a commercial test facility. The results of this test are described in the following section. The test revealed about a 10% residual (permanent) volume increase in the tank after being pressurized to 8,100 psi. A subsequent test to 4,000 psi, showed no additional residual volume change. Based on this test, a decision was made to limit the sensor pressure tests to 4,500 psi. Between 2,000 psi and 4,500 psi tank pressure, it was hoped that the optical sensor might correctly detect nonlinear behavior with residual volume change.

LOW PRESSURE TESTS

In this series of tests, the optical fiber response of the tanks to pressure varying between zero and 1,000 psi was investigated. The objective was to determine if the signal is linear and repeatable and to compare the different sensor designs.

The tests were conducted with the tank isolated behind an 18 inch thick concrete/rock barrier. To minimize explosive energy from developing, the tank was hydrostatically tested with water. The test setup allowed elimination of most of the air in the tank, pump, fittings and pressure hose.

A 1/4 in. high pressure hose connected the tank to the pump with a pressure gauge at the pump outlet to measure the tank's internal pressure. The power output of the sensor was measured with a light power meter that attached to the fiber optic connectors. A needle valve at the tank inlet allowed air to be bled from the system prior to pressurization and an identical needle valve at the pump outlet provided pressure relief (Fig. 5-1).

Figure 5-2 shows Tank 2 with pressure fittings and optical leads. The tank was wrapped in paper to protect skin from the rough E-glass composite surface. On the right side of the tank are the pressure fittings and the bleed valve to eliminate entrapped air. On the left side of the tank are the optical connectors.

The tank was loaded and unloaded through six pressure cycles to a maximum value of 700 psi. Light power measurements were made at 100 psi increments. Six load cycles were completed with consistent light power readings. Figure 5-3 shows the readouts at 0 psi for the hand pump and 240.8 μWatts for the power meter. These readings are at the state of beginning a load cycle. Figure 5-4 shows the readings of the pump at 700 psi and light power meter at 225.6 μW for load cycle #4. The test data is listed in Table 5-1. A plot of this data in Figure 5-5 shows that the sensor response is nearly linear and very repeatable. The light power change from the initial measurement for each cycle is shown in Table 5-2.

The mean light power change and the standard deviations at each pressure increment are listed in Table 5-3. It was observed that the data had less variation when cycles 1 and 2 were neglected. This may indicate a break-in period where the composite overwrap "seats" against the aluminum liner. The mean light power change for the stabilized cycles 3-6 is plotted in Fig. 5-6. A small difference between the load (apply pressure) and unload (release pressure) portions of the load cycle is evident. Figures 5-7 thru 5-12 plot the percentage light power loss for Tanks 2, 3 and 4 for a number of load cycles and the mean value of the light power loss for loading and unloading.

Figure 5-13 is a compilation of the foregoing Mean Light Power Loss curves for Tanks 2, 3, and 4. In Fig. 5-14, the plots are extrapolated to a tank pressure of 3,000 psi to help evaluate selection of number of pinch points for Tanks 5 and 6. These extrapolated curves were then adjusted to show

Mean Light Power Loss per Pinch Point as shown in Fig. 5-15 by use of Eq. 2-2. This plot reveals that Tank 2 with 49 epoxy-filled pinch points produced the largest signal per pinch point. Next, points from the Tank 2 curve in Fig. 5-15 were transformed with Eq. 2-2 to produce the Fig. 5-16 plots of Light Power Loss as a function of the Number of Pinch Points at 1,000 psi, 2,000 psi, and 3,000 psi. At an anticipated tank working pressure of 3,000 psi, this plot shows that a 75% signal loss could be achieved with about 200 pinch points.

Based on the data obtained from the Tank 2, 3 and 4 tests, it was decided that Tanks 5 and 6 will use 202 epoxy-filled pinch points to provide a desirable 75% light attenuation signal.

HIGH PRESSURE TESTS

Tanks 2, 3, 4 and 6 were tested at higher pressures for 10 load cycles. On the eleventh load cycle, the tanks were tested at a commercial hydrostatic test facility to measure volume change. These tests are described in the following section.

The Tank 2 (49 epoxy-filled pinch points) Light Power Loss plots for cycles 1-10 are presented in Fig. 5-17. Cycles 1 and 2 were taken to 2,500 psi with hysteresis in cycle 1 and little hysteresis in cycle 2. The tank pressure was increased to 3,000 psi for cycles 3 and 4 with a similar behavior as cycles 1 and 2. In cycle 5, the pressure was increased to 3,500 psi and the hysteresis curve appears to be pronounced. This behavior was due to one optical connector loosening during the test. After reseating the connection, the test resumed with cycles 6 - 10 exhibiting a nearly linear response with small hysteresis.

The curves presented in Fig. 5-17 show that the composite overwrap "reseats" against the aluminum liner with each increase in pressure. Subsequent cycles at the same maximum pressure did not

produce noticeable hysteresis. Thus, the tank does require a break-in period before light power readings can be taken.

Figure 5-18 shows a similar trend for Tank 3 (52 Mylar-isolated pinch points). The upper envelope of curves for cycles 1-5 bounds nicely the hysteresis effect of increasing pressure. Tank 3 was broken-in over these cycles by gradually increasing the maximum pressure to 4,500 psi. By the 5th cycle, about an 11% residual light power reading was observed. This test shows that for a 5% or less residual light power loss, the tank pressure should not exceed 3,500 psi.

The Tank 4 (202 polyurethane-filled pinch points) test is shown in Fig. 5-19. For this test, the first pressure cycle was limited to 3,000 psi. Hysteresis is present with about a 5% residual light power reading. In terms of DOT requirements, this is the safe limit for composite tanks. Cycle 2 also was taken to 3,000 psi, but hysteresis is nearly absent. This behavior was observed in all tank tests. The composite overwrap "seats" itself with each increase in pressure. Subsequent load cycles to the same pressure produces a nearly linear, repeatable optical signal. In load cycle 3, the pressure is increased to 3,500 psi with an attendant increase of hysteresis. Subsequent load cycles to 3,500 psi again show a nearly linear, repeatable light signal without hysteresis.

The Tank 6 (202 epoxy-filled pinch points) test is shown in Fig. 5-20. The tank was pressurized to 4,500 psi In the first load cycle. Cracking noises were heard as the composite overwrap seated itself against the aluminum liner. As expected, the hysteresis was very large with a 55% residual light power loss. Clearly this test shows that the fiber sensor detected permanent structural damage. Load cycle 2 to the same pressure produced a nonlinear light power response with a residual loss of about 11% (after relaxation). Again, the large residual suggests additional structural degradation. For cycles 3 to 10, the maximum pressure was reduced to 3,000 psi. For these load cycles, nonlinear behavior

tracked cycle 2 with always about a 5% residual light power loss. This test confirms the ability of the fiber optic sensor to detect structural damage.

The Cycle 10 test data for each tank is plotted together in Figs. 5-21 and 5-22. These curves represent the sensor response after each tank had been fully conditioned (composite overwrap seated against aluminum liner).

As Fig. 5-21 shows, all the tanks exhibit fairly linear behavior below 3,500 psi. As expected, we see that the greatest power loss comes from the Tank 3 Mylar-isolated sensor. In fact, the power attenuation reaches nearly 85% at about 3,500 psi, which probably is excessive. The Tank 2 epoxy-filled sensor with 49 pinch points responded with a 50% light power loss at 3,500 psi compared with almost a 90% power loss for the Tank 6 epoxy-filled signal with 202 pinch points.

Using Eq. 2-2, the data in Fig. 5-21 is modified in the plot of Light Power Loss per Pinch Point presented in Fig. 5-22. The validity of the these tests is confirmed by curves for Tanks 2 and 6, both with epoxy-filled pinch points. The curves are collinear even though Tank 6 had four times as many pinch points as Tank 2.

Other observations can be made. The Tank 4 polyurethane-filled pinch points produced the smallest signal and the most linear signal. The Tanks 2 and 3 epoxy-filled pinch points produced a significantly greater signal with a slightly nonlinear behavior. The largest and most nonlinear behavior came from the Tank 3 Mylar-isolated pinch points.

VOLUMETRIC HYDROSTATIC TESTS

TANK 1

To determine a safe test pressure for testing the fiber optic sensor, Tank 1 (with defective sensor) was tested to determine its burst pressure. Tanks 1, 3, 4 and 6 were identically fabricated so the same test pressure could be used safely. The composite hoop wrap for Tank 2 is only one-half that of Tank 1, so the maximum test pressure for Tank 2 was limited to 3,500 psi. This is well below the expected tank burst pressure (see following discussion).

Fig. 5-23 is the burst pressure test for Tank 1. The test facility was unable to fail the tank due to equipment limitations. The maximum pressure reached was 8,000 psi. The technician conducting the test estimated that the burst pressure would be in excess of 12,000 psi based on the small 10% residual volume after releasing the test pressure.

The red line in Fig. 5-23 is the initial slope of the curve. It reveals that the volume change departs from nonlinearity beginning at about 2,500 psi. This is close to the finite element model prediction of about 2,000 psi.

TANKS 2, 3, 4 & 6

Following the light sensor tests described in the previous section, Tanks 2, 3, 4 and 6 were hydrostatically tested at a commercial test facility. The data for these tests applies to load Cycle 11 for each of these tanks. The plots of this data are given in the following section along with the fiber optic sensor data.

TANK TEST FINDINGS

Light power loss and volume change tests were performed on all tanks. The data for both types of tests were normalized with the corresponding maximum test readings, and plotted on the same graph. The closeness of the two curves is a measure of how well the optical fiber simulates tank volume change for both the loading and unloading parts of each curve. The light power curves are for load cycle 10 and the volume change curves are for load cycle 12 for each tank. The red curves in each plot refers to the left ordinate (Light Power Loss) and the blue curves refer to the right ordinate (Volume Change).

TANK 2

Figure 5-24 is the result obtained for Tank 2. Both light power and volume change behavior is close to linear and the curves are in close proximity. This tank with epoxy-filled pinch points simulates volume change reasonably well.

TANK 3

Figure 5-25 show that the Mylar-isolated pinch points exhibit a nonlinear trend whereas the tank volumetric change is very linear. The difference between the curves is excessive and suggests that Mylar isolation of pinch points should not be used.

TANK 4

Figure 5-26 reveals that the polyurethane-filled sensor nearly identically tracks volumetric change. This sensor provided the most linear and accurate tracking of volume change.

TANK 6

Figure 5-27 shows again that the volumetric response is linear and the epoxy-coated fiber sensor produces a significantly nonlinear response. The response of this sensor does not track volume change as well as Tank 2. This is most likely due to the initial damage to the tank sensor when the tank was over-pressurized in the first two load cycles (Fig. 5-20). For this reason, the response of Tank 2 might be more indicative of potential sensor performance.

DISCUSSION

Five prototype tanks were hydrostatically tested. Tank 1 was tested to 8,000 psi to ascertain that the remaining tanks could be tested safely at 4,500 psi. The remaining four tanks were tested for sensor performance. A sixth tank was intended to be tested for sensor performance, but damage done to the optical connector by the fabricator prevented its use.

The number of pinch points and method of filling the fiber pinch point areas were varied as design parameters. Three types of pinch points were used. Mylar isolators that prevented epoxy bonding of the optical fibers at pinch points proved to produce the largest optical signal. Based on tests of small specimens, this behavior was expected (Fig. 2-9). Next, polyurethane was used to encapsulate pinch points and prevent epoxy intrusion during filament winding. Although the sensor signal was nearly half that of the Mylar isolators, it nevertheless was a sufficient signal that was both linear and repeatable. The third sensor type is an epoxy-coated fiber. This method is considered advantageous since the composite overwrap has an epoxy matrix that would bond well with the coated fiber. By using more pinch points with this design, a sufficient signal is generated. Since the encapsulating

epoxy is a more rigid material, fiber microbending is believed to be inhibited. To increase the optical signal, more pinch points are used.

The purpose of the optical fiber microbend sensor is to simulate the hydrostatic volumetric test required by the U.S. Department of Transportation for all composite tanks. If the fiber sensor could replace the hydrostatic test, the tanks could be tested in-situ at low cost and with no loss of use of the tank. Moreover, in-situ testing could be done more frequently than required by the DOT which could lead to extending the useful service life of composite tanks.

The fiber sensor must be able to reveal a residual change of light power following pressurization to the rated tank pressure that in normalized form agrees numerically with residual tank volume change. All of the tanks tested demonstrated this capability, but the Tank 4 polyurethane-coated fiber followed by the Tank 2 epoxy-filled fiber performed best.

These results suggest that the fiber optic sensor can be successfully integrated into the manufacture of composite tanks at low cost. The fabrication of the sensor and connector and their installation onto an aluminum liner potentially is a simple process. The tank liner first is attached to a sensor winding machine. The fiber is coated with either polyurethane or epoxy and wound onto the liner. Shrink tape is wrapped around the installed fiber and it is then thermally cured. Finally the connectors are attached to the fiber and the aluminum valve stem. The fiber system now is sufficiently rugged to handle and filament wind so that no change in manufacturing procedures would be needed.

Novel concepts developed in this program include, but are not limited to:

1. A low-cost, telecommunication single-mode optical fiber (Corning SMF-28) can function as an effective microbend sensor when placed in the wall of a composite tank. With microbend sensing, an

inexpensive, hand-held light power meter is all that is required to monitor the structural health of a tank.

2. The fiber sensor is contra-helically wrapped around an aluminum liner. The number of pinch points (fiber crossings) can be adjusted to control the microbend signal by the number of helical wraps.

3. By preassembling the fiber sensor and aluminum liner, the tank can be handled and filament wound using current manufacturing techniques.

4. Pinch points where the fiber sensor crosses itself can be filled with a material that regulates light power loss across the points. This has demonstrated the effect of isolating the pinch points, bedding the points with a soft material (polyurethane) or bedding the points with a hard material (epoxy). Isolation provides the largest signal (microbending) and epoxy provides the smallest signal.

5. A simple, economical method of coating the fiber with a bonding material (polyurethane or epoxy) while it is applied to the tank liner was developed.

6. A new optical connector that is about half the size of a commercial connector was developed and tested. Its small size helps to reduce mechanical damage to the connector when handling of the tank, it also made it possible to locate the connector on the valve stem of the tank. The connector adapts to existing ST-type optiware. To ensure that optical readings are repeatable, the connector uses a polarized connection so that the angular position of mating ferrules is maintained.

Although helically wrapping and bonding the fiber sensor to the tank liner is accomplished easily, attaching the connector poses automation challenges. An approach that is being considered is to manufacture a fiber sensor with preattached connectors that would be sold to tank manufacturers in predefined lengths. Instead of using a syringe to dispense the coating material as described, the fiber would be precoated with epoxy, polyurethane or other suitable bonding material for winding onto the

tank. The coated fiber would be kept in a tacky, uncured state at low temperature until ready for application to the tank liner. After winding the fiber onto the tank, it would be cured thermally or by use of ultra-violet (UV) light. Similar technologies already exist for prepreg composite fabrics. Assembly would proceed by first attaching a connector to the valve stem using a rapid cure adhesive. One or more layers would be helically wrapped onto the aluminum linear in a winding machine similar to the procedure depicted in Fig. 2-11. The second connector then would be attached to the valve stem, the cylindrical portion of the tank would be wrapped with shrink tape and finally the entire assembly would be cured.

The purpose of the optical fiber microbend sensor is to simulate the hydrostatic volumetric test required by the U.S. Department of Transportation for all composite tanks. If the fiber sensor could replace the hydrostatic test, the tanks could be tested in-situ at low cost and with no loss of use of the tank. Moreover, in-situ testing could be done more frequently than required by the DOT which could lead to extending the useful service life of composite tanks.

The fiber sensor must be able to reveal a residual change of light power following pressurization to the rated tank pressure that in normalized form agrees numerically with residual tank volume change. All of the tanks tested demonstrated this capability, but the Tank 4 polyurethane-coated fiber followed by the Tank 2 epoxy-filled fiber performed best.

While the invention has been described with reference to specific embodiments, modifications and variations of the invention may be constructed without departing from the scope of the invention, which is defined in the following claims.